Surface Effects of Radiation on Transistors*

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Observation of surface effects of ionizing radiation on several types of transistors indicates that in reverse-biased devices these effects occur at much lower radiation dosage than in unbiased devices or bulk semiconductor material. Further, the total radiation dose rather than dose rate seems often to be the more important factor in the effect. The type of particle used in irradiation is unimportant; the significant factor is the ionization it produces. The effects seem to arise from ionization of gases within a transistor encapsulation and interaction between the ionized gas and residual semiconductor surface contaminants. This results in inversion layers at the device surface and thus in alteration of junction characteristics. The changes in device properties are not permanent, but the recovery after removal from radiation is complex and proceeds with characteristic times between seconds and days.

Different types of devices may respond quite differently to exposure, and the response is different even between different batches and individuals, indicating a dependence upon device processing.

I. INTRODUCTION

A wide variety of effects of high-energy radiation on semiconductor materials and devices has been recognized and studied for a number of years. The major emphasis in this field has been on effects that involve the bulk properties of semiconductors. A great deal of progress has been made in understanding the processes that control bulk radiation phenomena[1] and in understanding the implications of these phenomena for semiconductor devices.[2] Radiation effects on semiconductor surfaces also have been observed,[3] and this paper is concerned with some special aspects of surface phenomena that have recently come to light. In contrast to bulk effects, the surface radiation effects are very poorly under-

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stood and in general even poorly characterized. This paper will attempt to shed a little light on these complexities and indicate a type of measurement program that has been found appropriate for dealing with devices intended for use in a radiation environment such as that of the Van Allen belts in space. It will fall short of providing a satisfactory understanding of the processes involved.

The paper is arranged as follows: in Section II, for perspective, a brief discussion of the two broad classes of bulk radiation effects is included. Section III describes the early observations that provoked the present work. Section IV is a proposed model of the basic process. Section V describes results of a number of experiments carried out to test the mechanisms of the process. Section VI characterizes effects with significant numbers of devices. Section VII describes the process of testing and selection undertaken for Telstar devices. Section VIII is a summary of the paper.

II. BULK RADIATION EFFECTS

Bulk radiation effects can be placed in two broad classes that arise from (a) hole-electron pairs produced in the crystal by ionizing radiation and (b) defects in the semiconductor lattice produced by high-energy particles. These phenomena often occur together but they result from quite different interactions of radiation with the solid and they have very different consequences in semiconductors.

2.1 *Hole-Electron Pair Formation*

Fig. 1(a) illustrates the first case. Any charged particle passing through a solid produces ionization through collisions with the bound electrons. These collisions excite electrons to the conduction band and leave holes in the valence band, producing electron-hole pairs in exact analogy with the production of pairs by light. Neutrons and gamma rays also cause ionization effects through intermediate reactions that produce charged particles. As far as effects which depend on ionization are concerned, the particular particle involved is incidental; all that matters is how much energy is lost in the solid. The number of hole-electron pairs produced is proportional to this energy loss.

The generated pairs tend to recombine with a time constant that is the conventional lifetime. Hence, all effects in this class are transient and persist only for the order of a lifetime after the excitation is removed. The pairs produced alter the conductivity of semiconducting materials. They also contribute currents in p-n junction diodes and transistors.

Under pulsed ionizing radiation these effects can alter conductivities and currents by many orders of magnitude. On the other hand these effects can be very small in response to a single energetic particle and special p-n junction diodes may be required even to detect them.[4] A case of intermediate magnitude has been considered by Rosenzweig[5] who has used silicon solar cells to measure the intensity of moderate radiation fields.

2.2 *Lattice Damage*

Fig. 1(b) illustrates the other type of bulk radiation effect in semiconductors that arises from collisions of energetic particles with the nuclei of the lattice. If such a collision transfers sufficient energy to the struck atom, it is capable of moving the atom from its normal lattice site to some interstitial position in the crystal. These events are rare by comparison with the ionization events of Fig. 1(a), but they create permanent or at least semipermanent defects in the structure of the lattice. The most important consequence of these defects is reduction in the carrier lifetime of the material. Increases in diode reverse current and decreases in transistor current gain are produced as functions of the time integral of the flux of particles. In contrast to the pair production of the paragraph above, this radiation damage is extremely dependent on the particular particle involved. Energetic protons, for example, are much more effective in producing damage than energetic electrons. This type of radiation effect is of major importance to the long-term power conversion efficiency of solar cells in space. Detailed consideration of this problem can be found elsewhere.[6]

III. THE SURFACE PROBLEM

Surface effects on semiconductor devices have an illustrious history of subtlety and perversity and it is no surprise to learn that radiation is an environmental factor that must be considered. Several years ago, before the present sophistication in surface processing, experiments were carried out in an attempt to characterize radiation surface effects[3] (changes in junction current, breakdown voltage, current gain, etc.). No systematic picture evolved, although surface cleanliness seemed certain to play some role.

Transistors that have evolved from refinements in junction formation and surface treatment techniques have, in the last few years, been examined in a variety of high-energy neutron and gamma-ray environments. Particular attention has been given to bulk radiation damage

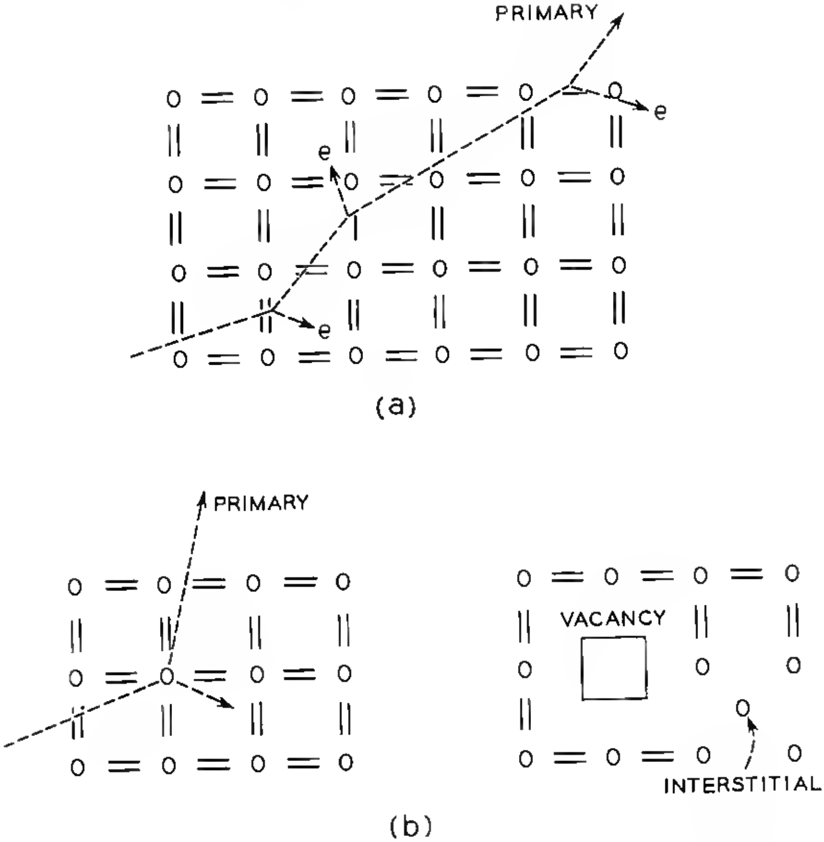

Fig. 1. — (a) Production of hole-electron pairs by collision of a charged particle with electrons of a semiconductor. (b) Production of lattice defects by collision of particles with the nuclei of a semiconductor.

effects on current gain since these effects turned out to be serious (particularly for silicon) at the flux levels of current interest in the vicinity of nuclear reactors. Very substantial improvements in radiation tolerance have been found; however, no recent comprehensive work on the surface effects has been reported.

The relative stability of the characteristics of a particular type of diffused silicon transistor under radiation is illustrated in Fig. 2. The collector reverse current is displayed because it is a particularly sensitive indication of surface stability at the very low currents that are conventional in present silicon devices. The gamma-ray radiation* used in this

* Radiation dose is frequently measured in "rads," which are a measure of the

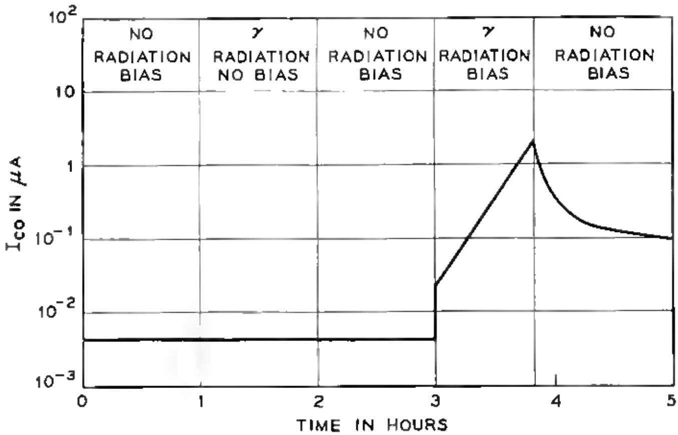

Fig. 2. — The response of I_{CBO} of a diffused silicon transistor to either radiation or bias alone or to both together. Radiation dose rate 8.5×10^5 rads/hr.

case is representative of ionizing radiation in general. The figure shows that after one-hour tests with neither bias nor radiation or with either alone, the current is essentially unchanged. (Actually much longer tests under bias are conventionally made in checking device reliability with the same result as shown here.) However, when bias and gamma radiation are simultaneously applied two effects appear: there is a sudden rise in current and then an upward drift of current over many minutes. The sudden rise of about 0.02 μa is largely due to ionization of the gas in the device can. The current drifts upward by another decade in the 45-minute exposure following its rapid rise. When the gamma radiation is removed the current does not immediately drop back to its pre-irradiation value, but gradually declines and even after an hour is more than a decade too high. A drop of about 0.02 μa must still occur at gamma-ray turnoff, but this is so small compared with the level to which the current has drifted, that the drop is not visible.†

The drift up and the slow decay of the collector currents are surface effects produced by the radiation only when the collector junction is reverse-biased. This aspect of radiation sensitivity had not previously

energy absorbed per unit mass of material. One rad is equivalent to absorption of 100 erg/gm. Such a dose would produce approximately 2×10^9 ion-electron pairs/cm^3 in atmospheric air or about 4×10^{13} electron-hole pairs/cm^3 in silicon.

† Ion currents to the electrical leads either in the device encapsulation or in the gamma radiation chamber pose a serious problem to measurements on devices at very low leakage currents in high radiation fields (10^5-10^6 rad/hr). It has often proved necessary to remove the device from the radiation environment momentarily for measurement. Because of recovery effects care must be taken to obtain measurements quickly and at uniform times after removal.

been reported. It represents a factor that must be considered for reliability of devices that must operate in any radiation environment including the high-energy electron and proton belts found in outer space. The conclusion that these effects arise at the semiconductor surface can be reached in a number of ways. If they were bulk effects the marked influence of applied bias is quite unreasonable. Radiation defects created in a solid have been influenced by extremely high electric fields, but only to the extent of causing them to migrate very short distances in long times.[7] Furthermore, the decay of the effect occurs in a time that is very short for defect annealing in silicon. But more convincing is the sensitivity of the effect to the surface environment of the device inside its encapsulating can.

Fig. 3 shows four typical npn diffused silicon transistors of two types, each with two kinds of ambient atmosphere. Increases in collector current are observed in all four, but at quite different integrated gamma-ray doses. In both device types early current increases are associated with gas filling. In type B the evacuated device shows no measurable change until the integrated dose is in a range expected to cause substantial decreases in bulk lifetime. In this case, the influence of bias, although not shown in the figure, is practically nonexistent.

Not only is there a variation in the response depending on the gas filling of transistor cans, but there is also great variability among devices with a single type of filling. All evacuated units are slow to respond, but in the type B transistor only about half of the gas-filled units respond quickly. The other half are almost as stable as the evacuated

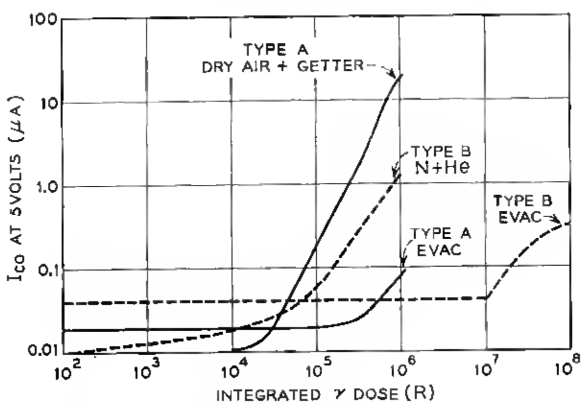

Fig. 3. — The radiation degradation of I_{CBO} of two types of diffused silicon transistors, evacuated or with gas filling. Radiation dose rate 8.5×10^5 rads/hr.

units. This points again to a surface effect and to a broad spread in response arising from rather subtle differences in the surface chemistry. This lack of reproducibility complicates the study of the process involved and necessitates the use of statistical experiments, some of which will be reported in later sections.

Before continuing to discuss the experimental observations we will introduce a simple model which describes some, but not all, of the effects, and provides a framework for the later discussion.

IV. A MODEL OF THE PROCESS

Radiation, gas encapsulation, and device bias that seem to be essential to the effects shown in Section III can be combined in a simple model of the process. Fig. 4 illustrates the ingredients: the fringing field of a reverse-biased collector junction on an npn transistor and ions and electrons produced by gamma radiation in the gas of the encapsulation. The fringing field separates the electron-ion pairs, depositing electrons on the collector side of the junction and positive ions on the surface of the base. On both regions these charges tend to produce inversion layers at the surface, the effects being analogous for pnp and npn devices. For simplicity only the inversion layer on the p-type base of a npn transistor will be considered. A magnified view of the edge of the device might be as shown in Fig. 5. The positive ions induce an electron-rich inversion layer or "channel" on the base and in effect extend the collector region

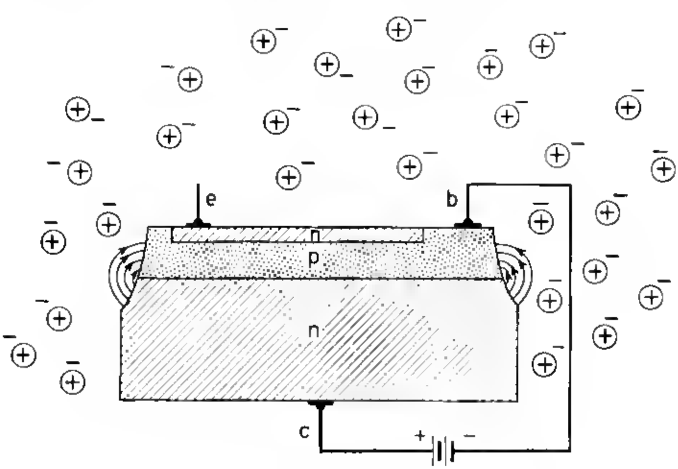

Fig. 4. — A model of a reverse-biased transistor in a gas atmosphere ionized by radiation.

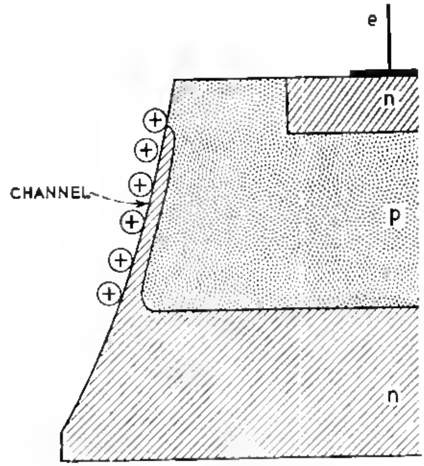

Fig. 5. — Formation of a channel on the base of a transistor by positive ion collection on the surface.

out over the base. The channel represents a grossly different surface than existed before. Since the junction between the electron-rich channel and the base material constitutes an extension of the collector-base junction, it contributes to the collector saturation current. In part this is simply because of the extra junction area. More importantly, because the channel junction is very close to the surface, the surface generation process can yield much more current per unit area than for the junction in the bulk. Furthermore, if the channel extends to the emitter it can add additional current to the collector by serving as a conducting path between the two. Channel effects on transistors and diodes have been studied previously in considerable detail[8] entirely unrelated to the presence of radiation. The basic channel characteristics of emitter-to-collector conductance, high emitter floating potential, and channel pinchoff have all been observed in connection with the present surface radiation effects on diffused silicon transistors.

We have so far considered only formation of a channel by charge collection in the collector fringing field, but a second possibility is shown in Fig. 6. In all the npn diffused silicon transistors used in these experiments the collector is electrically tied to the encapsulating can of the device. Under collector reverse bias a field then exists throughout the whole can of such a sign as to drift positive ions toward the surface of the device base. This feature can be expected to increase the ion-collection efficiency.

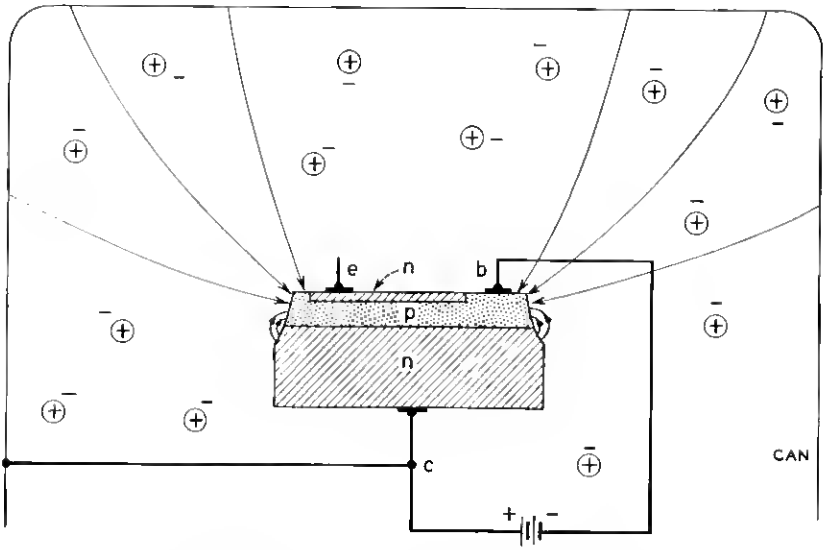

Fig. 6. — The enhancement of ion collection at a transistor surface due to electron fields between the device and its encapsulating case.

One may ask if there are enough ions produced in the gas of the can, by the radiation doses that have been used, to provide large channel effects. At an integrated dose of 10^4 rads (at which these effects may be substantial) and at atmospheric gas pressure (the normal device filling) a total of about 2×10^{13} ions per cc will have been produced. With a device enclosure of about 3×10^{-3} cc and a base layer area of about 10^{-3} cm^2, if all the ions were collected on the base, their concentration would be about 10^{14}/cm^2. On typical base material only about 10^{11} surface charges/cm^2 will be required to produce a channel. These several orders of magnitude margin are probably quite important because the efficiency of the surface charging process seems likely to be quite low. Furthermore, the process is far from a perfect charge integrator as we shall have occasion to observe in connection with reciprocity experiments in Section 5.2.

The lack of reproducibility noted in Section III in connection with devices of the same type and same gas filling seems to necessitate an elaboration on the model. If ions of the gas are sufficient to produce a channel, why are there some devices with gas that are as stable as devices without? The gas ions themselves must not be the tenacious charge on the surface that forms the channel. The gas ions probably

exchange their charge with residual contaminants on the device surface. Ionization of the surface contaminants directly is apparently too rare to be observed, since vacuum-encapsulated devices show uniformly high surface stability. This is roughly reasonable since the probability of ionization of any single atom is estimated to be only about 10^{-5} at 10^4 rads. Even with a monolayer of residual surface contamination, the surface ion concentration would then be only about $10^9/\text{cm}^2$. Of course, if the gas ions are to do the job, they must be reasonably effective in finding and exchanging charge with the residual impurities. There seems to be margin for inefficiencies in these very rough numbers.

This model predicts a number of effects that can be tested:

1. The effect depends only on ionization, not on incident particle type.
2. The simplest form of the model suggests that the effect is cumulative and depends on total dose, not on dose rate.
3. The effect should be more pronounced at higher collector bias.
4. The electric field between the can and the semiconductor may influence ion collection.
5. The decay of the effect should be faster if the device is not under continuous bias and should be accelerated in the presence of radiation without bias.

The results of the experimental tests of these predictions are contained in the following section.

V. TESTS OF THE MODEL

5.1 *Ionization*

If ionization in the gas of the device encapsulation is essential, then just as in the case of the ionization effect in a semiconductor discussed in Section 2.1, the type of energetic particle should not matter. The experiments in Section III were carried out with Co^{60} gamma rays which ionize through photo or Compton electrons that they produce. We have tested the model by comparing the results of 18 Mev proton irradiation with the Co^{60} gamma rays. The individual device response scatters so widely that the behavior of a number of similar devices is examined in each case. Fig. 7 shows the collector reverse current versus radiation dose, for gamma rays in dashed lines and protons in solid lines. The dose is calculated simply from the amount of energy deposited in a gas (the gas of the encapsulation) by gamma rays and protons. The radiation intensity (dose per unit time) was approximately 10^6 rads/hr for the protons as well as for the gamma rays.

Within the spread of response observed, there is no significant differ-

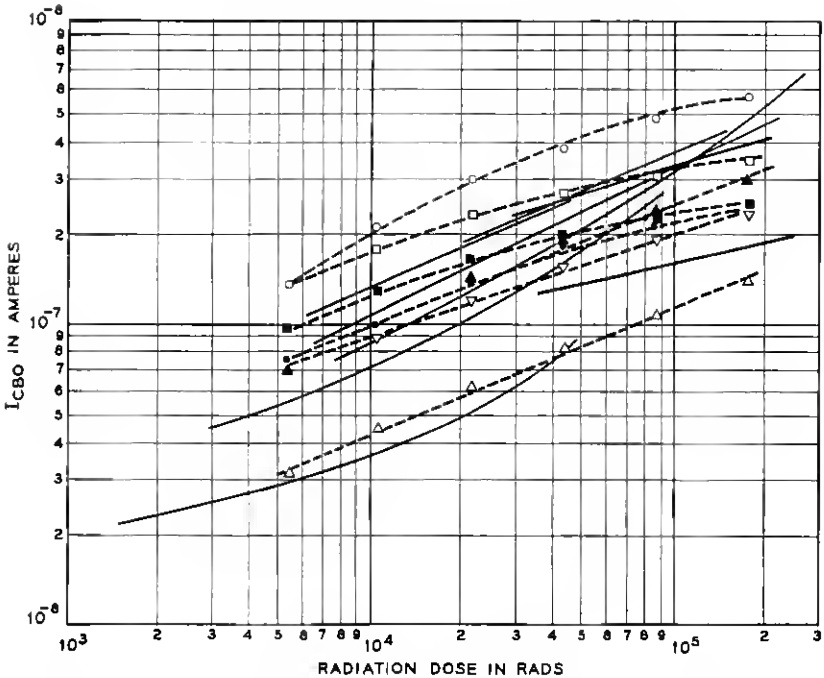

Fig. 7. — Comparison of I_{CBO} changes under radiation by gamma rays (dashed lines) and protons (solid lines).

ence between protons and gamma rays. If bulk damage in silicon were involved, one could expect a factor of 10 to 100 greater effect for the protons than for the gamma rays. (The bulk damage effect per particle comparing 18 Mev protons and 1.25 Mev gamma rays would be a factor of 10^4 to 10^5, but the scale in Fig. 7 is not particles but ionization, or energy loss, and the protons lose energy at a much higher rate than gamma rays.) We conclude that ionization is essential to the mechanism of this surface radiation effect.

5.2 *Reciprocity*

The surface ionization effects may depend only on the total radiation dose or they may also depend on the dose rate. In the first case there is reciprocity between dose rate and time. Information on this point is relevant to understanding the process and is of immediate practical importance as well. The experiments are most easily performed at high dose rates, but the device reliability is also of concern in modest radiation fields.

In Fig. 2 recovery of the collector current following radiation is illustrated. The fact that recovery occurs at all when a device is removed from radiation but kept on bias proves that the observed result does not depend solely on the total dose. The ionized state of the surface at any time is not simply related to the total number of ions that have reached that surface.

Fig. 8 shows the change of collector current vs dose at two different high dose rate levels. The experiment was started at 8×10^5 rads/hr. After approximately half a minute, when a dose of 6×10^3 rads had been delivered, the transistor was placed inside a lead shield that attenuated the gamma radiation by a factor of six. When a dose totaling 1.8×10^4 rads had been given the device, the attenuator was removed and the higher level radiation continued. After each attenuator change, the collector current continues to rise in a smooth extension of the earlier portions of the curve. If the dose rate were important, the middle segment of the curve would be expected to have a different slope than the two ends. During the attenuator changes the device was out of the radiation for approximately a minute and the current had started to recover, as indicated by the first point taken at the lower dose rate. A comparable drop would have appeared at the second attenuator change, but the

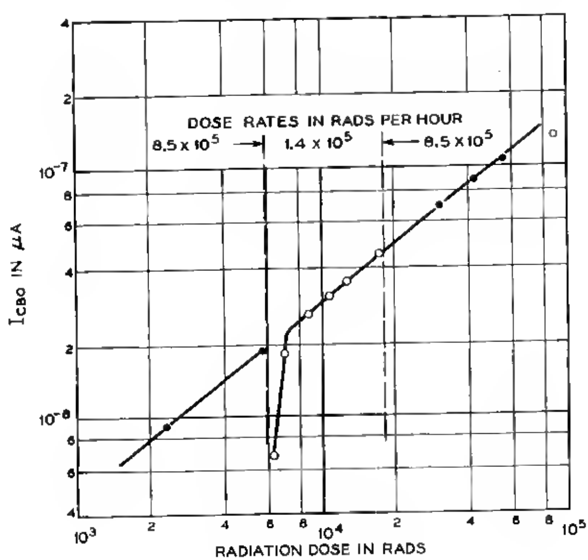

Fig. 8. — Reciprocity of dose rate and time at two high radiation dose rate levels.

earliest measurement after reinsertion in the radiation field was not obtained soon enough for it to show.

The rapid reestablishment of a previous high response to radiation, after some recovery from it, represents a memory in the process. This kind of memory has been seen repeatedly. Devices that were irradiated and have apparently completely recovered their original collector characteristics by standing out of radiation and even off bias, will still tend to reestablish their former response on a second radiation exposure. Even after several weeks, a device seems to retain a sensitivity to subsequent radiation as a result of an earlier exposure. There is some evidence that the memory can be removed by baking at approximately 100° C for a few hours.

The ionization produced by the radiation apparently has two functions: first, to produce some chemical species that are capable of ionization and second, to keep these species in an ionized state. The number of these centers would reflect the total radiation dose, but some minimum level of radiation would be required to keep them active.

We can draw the conclusion from Fig. 8 that, in the high-intensity region, dose is the important variable. Fig. 9 illustrates quite a different

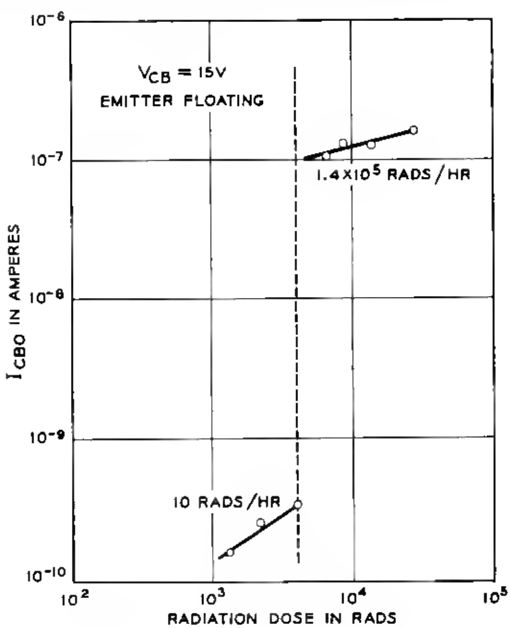

Fig. 9. — Lack of reciprocity between high and low dose rates.

range. Here a device started its radiation history at only 10 rads/hr and established a pattern of current increase that is already determined at a dose less than 10^4 rads. Putting the device into the attenuated high-intensity source does not produce a simple continuation of the earlier curve, but rather produces a curve two and one-half orders of magnitude higher in current. This illustration is extreme and not many devices show this large a discontinuity, but essentially none give results that could be interpreted as simple reciprocity. Apparently over a dose-rate range this great, using the concept of the preceding paragraph, the ionization-sensitive chemical entities are not fully ionized in the low radiation field.

5.3 *Surface Effect vs Collector Bias*

Since the surface effects we have been considering are absent except under the simultaneous application of radiation and collector reverse bias, we expect to find that changing the bias will alter the effect. This can occur because of increases in efficiency of charge collection, but also because the increased junction field tends to bind the ions more tightly to the surface or distribute them to form a more extensive inversion region.

Fig. 10 shows the effect of a sudden change in bias from 5 to 15 volts. One gains the impression that the current suddenly adjusts to a level and to a rate of change that are what they would have been if the entire dose had been given the device at the higher bias. If this impression is valid it would indicate that the effect at higher bias had not been retarded by the initial dose at low bias, and hence that ion collection was no different. In a plot like Fig. 10 it must be realized that the significance of the first dose rapidly diminishes in comparison with the total as one moves out along the second branch of the curve. It does seem possible to infer that a given number of ions on the surface gives a larger current contribution at higher bias. Rearrangement in the new field and effective extension of the length of a surface channel can occur.

Fig. 11 shows the response of transistors under radiation at different biases. Up to a dose of about 10^4 rads the current increase depends strongly on bias. Between 10^4 and 10^5 rads the slopes of the curves on this log-log plot are quite similar. Although only 4 units are illustrated in Fig. 11, the total group in the experiment was 80 and this pattern of behavior was quite consistent. Even beyond 10^5 rads where the slopes increase there is considerable uniformity between individuals and across the voltage range. This point is illustrated in a different way in Fig. 12 where the median behavior of a group of 10 to 12 devices at each bias is

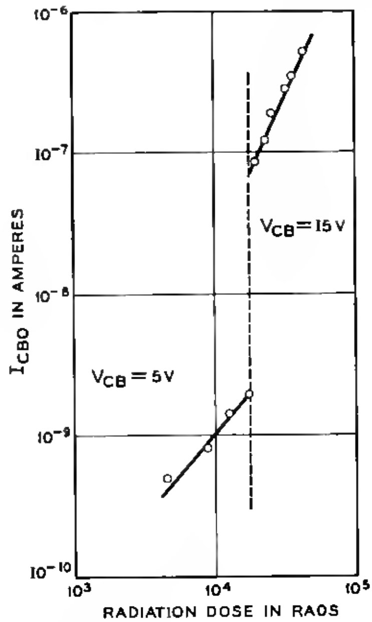

Fig. 10. — Influence of change in collector bias on degradation of I_{CBO}. Dose rate 8.5×10^6 rads/hr.

plotted at 6×10^3 rads and 6×10^4 rads. The pattern of bias dependence is already established at the lower dose and is smoothly maintained after the further order-of-magnitude change in dose. The lump at 10 volts appears to be significant. If it is real, its explanation will require a clever refinement in the model.

We do indeed observe the anticipated increase in device degradation at higher bias. The consistency of the shape of the voltage dependence at doses greater than 10^4 rads strongly suggests that the dependence does not arise only from a difference in the numbers of available surface ions, but also from variation in the arrangement of ions and the influence of this arrangement on the current characteristics of the channel. The collection of charge does not seem to be the dominant variable over the voltage range examined.

Another indication that junction bias affects the arrangement of charge on a device surface is shown in Fig. 13. The characteristics observed after a total dose of about 10^7 rads and at a high dose rate may show considerable structure, depending on the rate at which the characteristic is swept out. Furthermore, the differences between the charac-

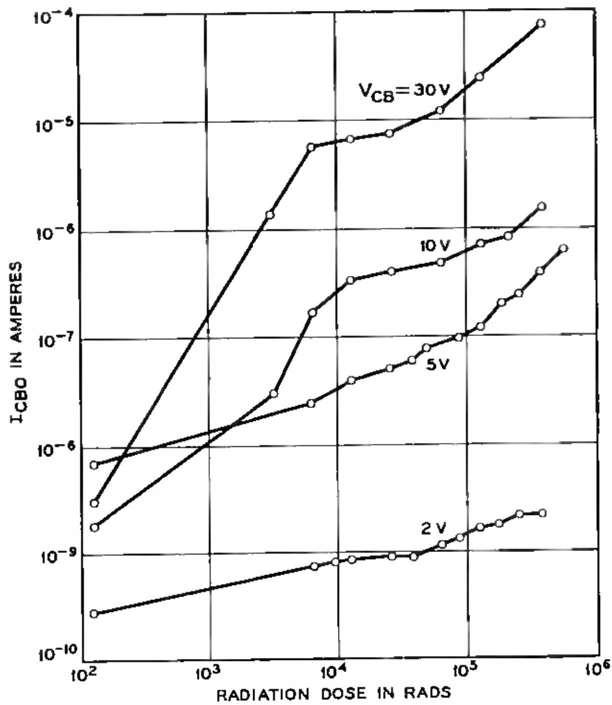

Fig. 11. — Dependence of degradation in I_{CBO} on collector bias.

teristics with slow and fast sweep show that rearrangements are not instantaneous. Note that here also a peak in I_{CBO} occurs in the vicinity of 10 volts.

5.4 *Influence of Can Potential*

It has been suggested that the electric field existing between the can and the transistor base by virtue of the bias on the collector junction may alter the collection of ions at the semiconductor surface. This possibility has been examined using diffused silicon diodes, encapsulated in the same gaseous atmosphere as the diffused silicon transistors. Devices with the p-region common to the can and others with the n-region common were studied. There was no substantial difference in sensitivity to ionization in these cases. On the other hand it was found that by alteration of the device processing, devices of either polarity were insensitive. It is clear that in this case the chemical surface condition is of more vital importance than the can-to-diode bias.

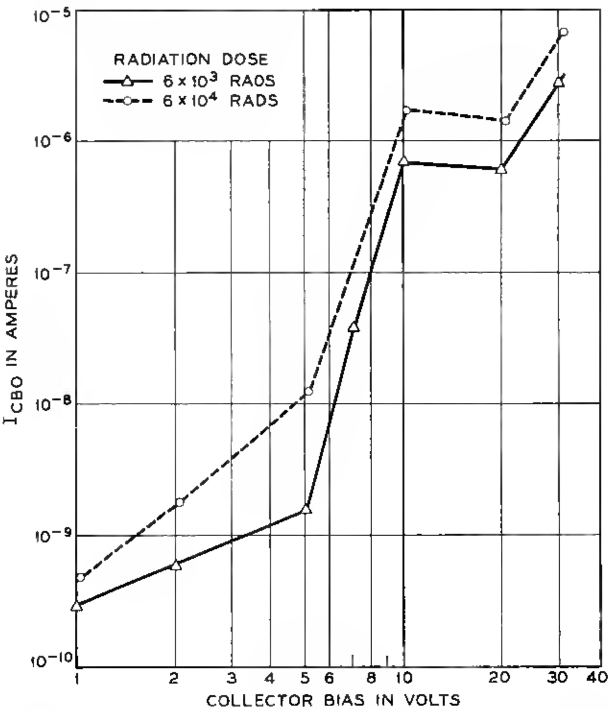

Fig. 12. — Median behavior of I_{CBO} with collector bias at two integrated doses.

No silicon transistor with reversible polarity to the can has been available, but a germanium transistor with all leads insulated from the can has been irradiated with reversal of the sign of can bias. The results are shown in Fig. 14. The device was irradiated at 8×10^5 rads/hr for one minute with the can negative with respect to the transistor base (the collector of which was continuously reverse biased) and then for one minute with the can positive and so on for longer times as the irradiation proceeded. The leakage current is very clearly much more sensitive to positive potential on the can than to negative, a result consistent with the original picture of the role of positive ions in a channel on the transistor base. This experiment has been repeated several times with some lack of reproducibility. In some cases can bias makes much less difference than as shown in Fig. 14 and in two cases where the whole radiation effect was smaller, the dependence on can bias polarity was reversed.

There seems to be no question that the can-to-device potential can be important, but clear-cut evidence that positive ions rather than electrons

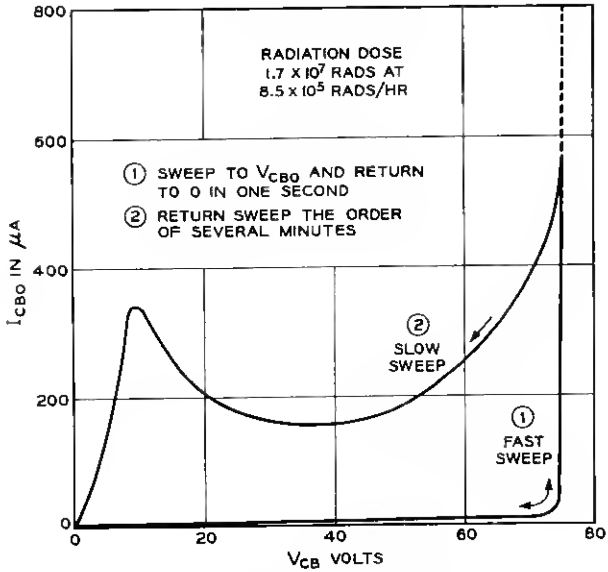

Fig. 13. — Structure and drift in the reverse characteristic of a heavily irradiated transistor under radiation.

(or negative ions) are always the important particle in transistor surface ionization effects has not been demonstrated.

5.5 *Recovery*

Recovery of the surface effects after an exposure to radiation has already been mentioned in connection with Figs. 2 and 8. The recovery is not exponential. In many cases, recovery under bias is well represented by a straight line on a log I_{CBO} vs log t plot, although the points at less than 0.5 min tend to fall below such a curve. The recovery represents a loss of charge at the surface, perhaps by neutralization from the interior in the absence of a radiation flux, but the memory effects suggest the active species do not actually leave the surface.

The comparison between recovery with and without bias is shown in Fig. 15. A transistor given a dose of 4.6×10^3 rads at 15 volts is shown, first recovering at this same bias and then recovering with the collector circuit open except momentarily for measurement. The decay is substantially accelerated in the zero-bias condition. This is consistent with the idea that the ions are bound in place by the field but in its absence are free to diffuse on the surface and will no longer be concentrated to produce an inversion layer It has also been observed that with reestab-

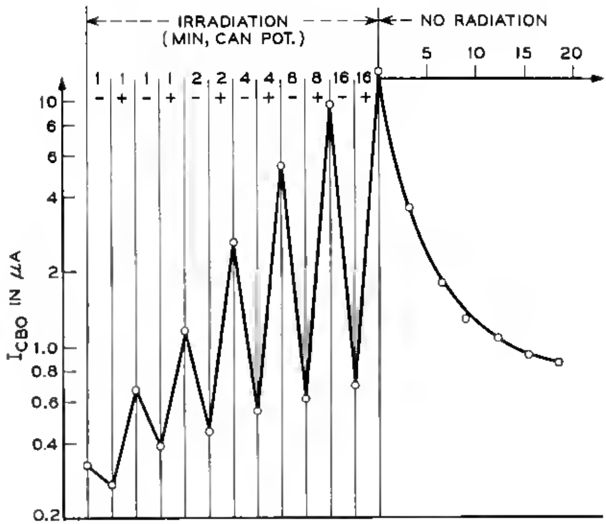

Fig. 14. — The influence of can-to-semiconductor potential on degradation in I_{CBO} of a germanium transistor.

lishment of the bias the current rises before continuing its decay, suggesting that the ions are subject to recapture by the field. There is a loss in this process however, that may arise from the enhanced neutralization of the ions by electrons from the inversion layer when they are more numerous in the absence of reverse bias.

Fig. 16 illustrates the effect of radiation on recovery. The upper curve was taken first and is a normal recovery with bias. The lower curve shows recovery from the same starting value in the 8×10^5 rads/hr gamma field without bias. The device is momentarily removed from

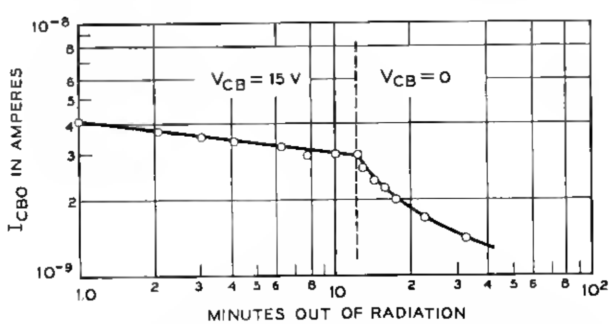

Fig. 15. — Decay of the radiation effect with and without bias.

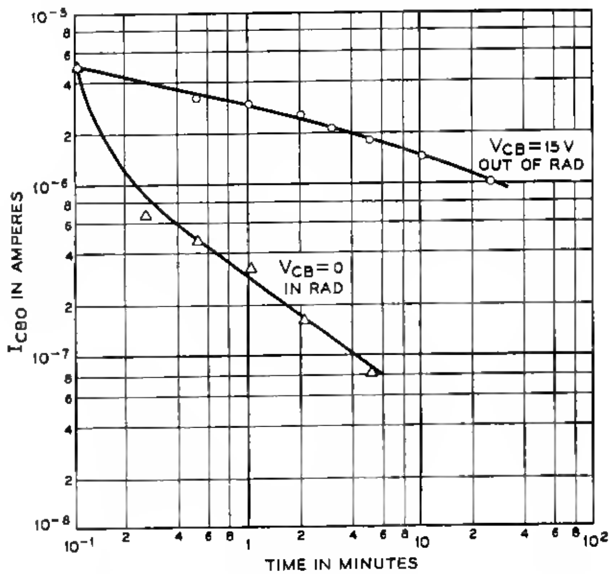

Fig. 16. — Enhancement of the rate of recovery of I_{CBO} with radiation but without bias.

radiation for measurement at 15 volts reverse bias. The recovery is substantially enhanced by the ionization in the absence of bias. This seems to be explained through neutralization of the charges on the semiconductor surface by the newly formed ions. Under bias the gas ions are directed by the junction field to strike the surface in places where they add to an inversion layer. In the absence of a field from applied bias, these ions tend to go wherever they can reduce fields produced by surface charges.

VI. CHARACTERIZATION OF EFFECTS WITH SIGNIFICANT NUMBERS OF DEVICES

With the above background concerning the surface effects of ionizing radiation, and with recognition of the limited knowledge of the range of exact surface conditions existing in semiconductor devices, further tests were planned to establish the extent of the ionization effect in larger samples of devices. For the purpose of such a test program, a transistor type was selected which showed particular sensitivity to the combined effects of electrical bias and ionizing radiation. These transistors normally have quite low collector reverse currents, I_{CBO} (in the order of

10^{-10} amperes). They are therefore good subjects for study at relatively low gamma dose levels since small increases in I_{CBO} can readily be recognized. A large number of devices were available with sufficient power aging to indicate stability of characteristics, so that changes could clearly be attributed to the radiation exposure.

Although the measurements of gain of these transistors under gamma radiation indicate some change with dose, the changes are relatively smaller than those in the junction reverse current and are hence less subject to recognition of a specific pattern of change. The data presented here, therefore, relate specifically to the changes in I_{CBO}.

6.1 *Typical Pattern of Degradation with Dose*

In order to determine the proper conditions for large scale evaluation, and to have some estimate of changes to be expected, it is desirable to establish the pattern of change in characteristics. From the data presented in Section V on the various factors affecting degradation, there develops a typical pattern of degradation, at least for the type of diffused silicon transistor used, as shown in Fig. 17. In this log-log plot of I_{CBO} vs integrated dose, four recognizable regions are indicated, an initial region of stability followed by three regions of change. The boundaries of the regions as indicated in Fig. 17 depict only representative variations and do not indicate actual limits of the device type.

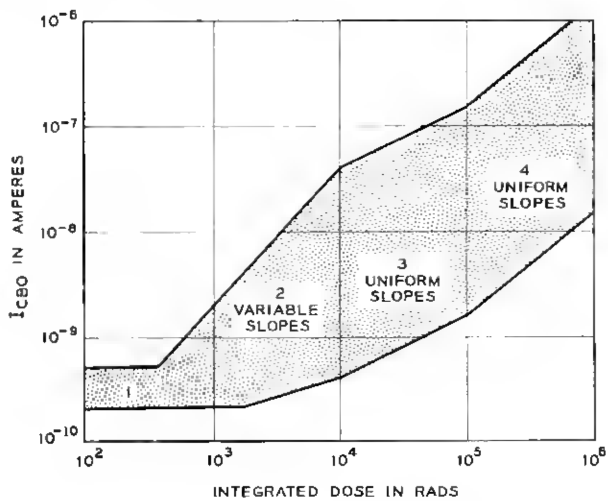

Fig. 17. — The typical pattern of I_{CBO} degradation under radiation for a particular type of diffused silicon transistor.

As discussed in Section 5.3, the slopes of the degrading I_{CBO}'s become quite uniform among all units of this type beyond a total dose of about 10^4 rad, or beyond the variable Region 2. In Region 3 all units show slopes of approximately $\frac{1}{2}$, and at about 10^5 rads there is a fairly distinct increase in slope which distinguishes Region 4. Although these two regions are recognizable, they are of lesser importance in judging comparative usefulness of the devices in radiation than are the region of stability and the slope in Region 2.

The region of stability is indicated even in the early tests (see Fig. 3) and continues to show up, even at the lowest initial current levels, when the dose rate is low enough to allow measurements at sufficiently low total dose. The extent of Region 1, or the dose value at which an individual unit starts to degrade, is quite variable among units of a type, as well as between types, and is a significant point for further consideration of devices.

The transition into Region 2, where the units show a typical linear increase in log I_{CBO} with log of dose, is quite distinct in all observed cases. For this reason, data which show only the degrading slope in Region 2 (perhaps because a high dose rate causes the first measurement to be beyond Region 1) can be extrapolated with some confidence back to the preradiation value to achieve an estimate of the transition dose. Major features of Region 2 are extreme variations between individual devices of a type and considerable dependence on collector voltage. This dependence is shown in Fig. 11 by the variations in I_{CBO} values achieved at about 10^4 rad, apparently about the end of Region 2 for this type.

In general, there appears to be a consistency between Regions 1 and 2 in that those units which show the greatest change in Region 2 also tend to indicate the shortest period of stability in Region 1; and conversely, those showing smaller changes in Region 2 appear to have the longer period of initial stability. Within the range of actual initial values (from 8×10^{-11} to 2×10^{-9} amperes) however, there appears to be no correlation between the initial value and the subsequent severity of degradation.

6.2 *Distributions of Dose at Initiation of Degradation*

With the recognition of the typical response of this transistor type to radiation, a question can first be asked regarding the variability in the extent of the region of stability, Region 1.

Fig. 18 shows several plots of the distribution, on a normal probability scale, of the integrated dose at which degradation is initiated (the end of Region 1). The three lowest curves show the results obtained from ex-

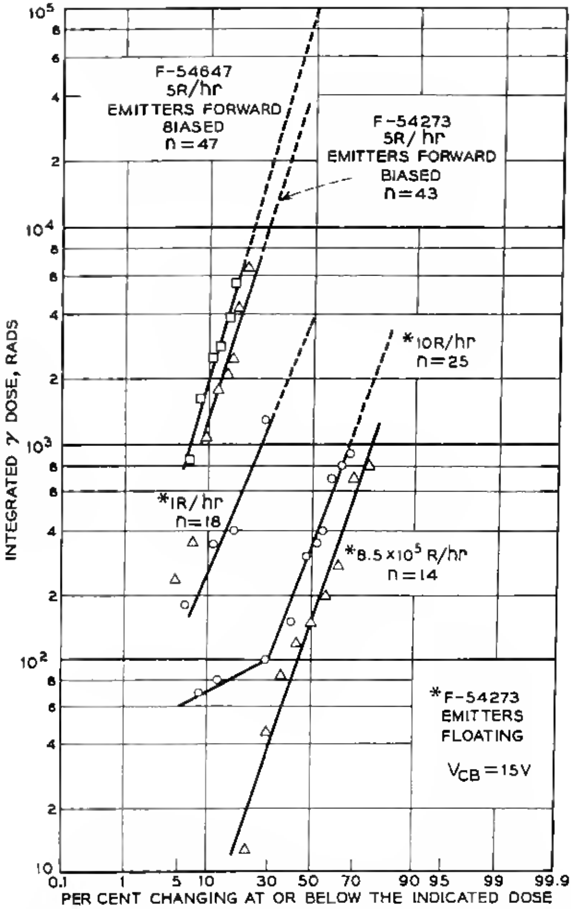

Fig. 18. — Distribution of the radiation dose at initiation of degradation.

posure to gamma radiation at 8.5×10^5 rads/hr., 10 rads/hr., and 1 rad/hr., all with a collector bias of 15 volts and with no connection to the emitters. There appears to be only about a factor of 2 difference between the 8.5×10^5 rad/hr. and the 10 rad/hr. results. This evidence of reciprocity between the 8.5×10^5 rad/hr. dose and the 10 rad/hr. dose at the end of Region 1 is in contrast to the lack of reciprocity indicated in Fig. 9 which compares reverse currents in Region 2. On the other hand, the difference between the 1 rad/hr. and 10 rad/hr. distributions seems to indicate a breakdown of reciprocity, at this level, in the dose required to initiate degradation.

The two upper curves of Fig. 18 are obtained at 5 rad/hr. and with a forward bias on the emitters during radiation in addition to the reverse collector bias. One of these curves is on the same transistor type (F-54273) as that of the lower distributions. The other distribution at 5 rad/hr. is on another transistor type (F-54647) which is basically the same but with a somewhat higher distribution of initial current gain. It would appear that the application of forward emitter bias causes an increase of roughly two orders of magnitude in the dose required for the onset of I_{CBO} degradation. This could result from the neutralization of positive charges on the surface of the base region by electrons injected into the base by the forward biased emitter.

6.3 *Distributions of I_{CBO} Increase*

Fig. 19 shows the distribution of the increase in collector reverse current resulting after 1.4×10^4 rads, which dose is past the completion of the variable Region 2. Here the I_{CBO}, on a log scale, is plotted on the normal probability scale. These data are on the same types of units represented in Fig. 18 and are obtained from radiation with the emitters forward biased. As in Fig. 18, the higher-gain type evidences a lesser degradation, having a longer region of stability as well as a smaller increase in I_{CBO} during Region 2. The excellent match to a log-normal distribution (except at very low currents where the data reflects the inaccuracy of measuring the difference between two nearly equal numbers) lends confidence to the interpretation that the break at the upper end of the distribution is caused by the transition into Region 3 of those units which have changed the most in the variable Region 2.

The broad distributions of Figs. 18 and 19 point up the necessity for relatively large-scale experiments in order to make valid comparisons between different test conditions or device types.

6.4 *Tests of Other Semiconductor Devices*

Similar kinds of distributions and general responses to the various conditions affecting degradation under radiation have been found in other codes of diffused silicon transistors and silicon diodes which have been encapsulated with a gas filling.

Fig. 20 shows, for example, the distribution of reverse current increase of a $\frac{1}{4}$-watt diffused silicon diode after 3.7×10^4 rads at 7.4×10^5 rads/hr. The broken shape of the distribution may simply indicate that the devices did not come from a single product run. The lack of the distinct break in the distribution at high currents suggests that the

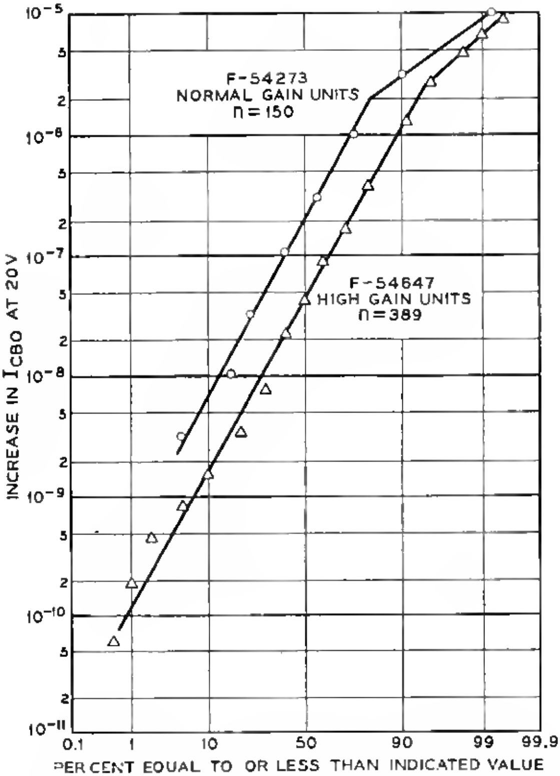

Fig. 19. — Distribution of current degradation after a dose of 1.4×10^4 rads at 8.5×10^5 rads/hr.

transition to Region 3 may not exist, or exists at a different dose. It would appear that each type must be examined in detail for a good understanding, even empirical, of its performance under radiation.

One interesting variation to the kind of response indicated above is that of a type of silicon alloy transistor which contains a silicone grease. In this case a relatively minor degradation is observed during short periods at a high gamma dose rate, but more severe degradation occurs during the period subsequent to completion of the exposure. This is indicated in Fig. 21, a plot of collector reverse current vs time after repeated exposures on an individual device. The device was exposed for several consecutive periods at 1.4×10^5 rad/hr., with current measurements subsequent to each exposure. The procedure was then continued at 8.5×10^5 rad/hr. Here each curve represents the I_{CBO} measurements subsequent to radiation for the total time indicated on the curve. I_{CBO}

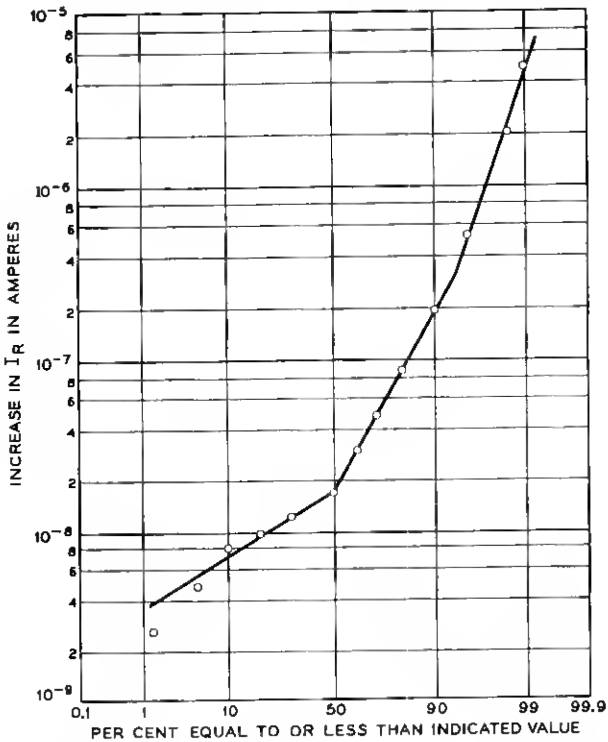

Fig. 20. — Distribution of degradation of current in a type of diffused silicon diode at 3.7×10^4 rads.

increases subsequent to the exposure, but may actually be decreased during the next exposure. After sufficient exposure, the devices evidence a saturation of the subsequent I_{CBO}, and also a saturation of the effect with continued exposure.

This saturation effect is confirmed at the 5 rad/hr. dose rate in Fig. 22, showing the I_{CBO} curves vs integrated dose for two typical transistors of this type. Both show an eventual saturation of the curve and one shows an ultimate reduction which appears also to be typical of this type of transistor.

Several types of diffused germanium transistors have also been examined, with the general result that increases in I_{CBO} are relatively small (of the order of a factor of 3 or 4), and relatively consistent, until the dose reaches about 10^6 rads, where more drastic increases may be expected. The dependence on V_{CB} was relatively insignificant. The effect of processing is evident in these types, however, with one group showing

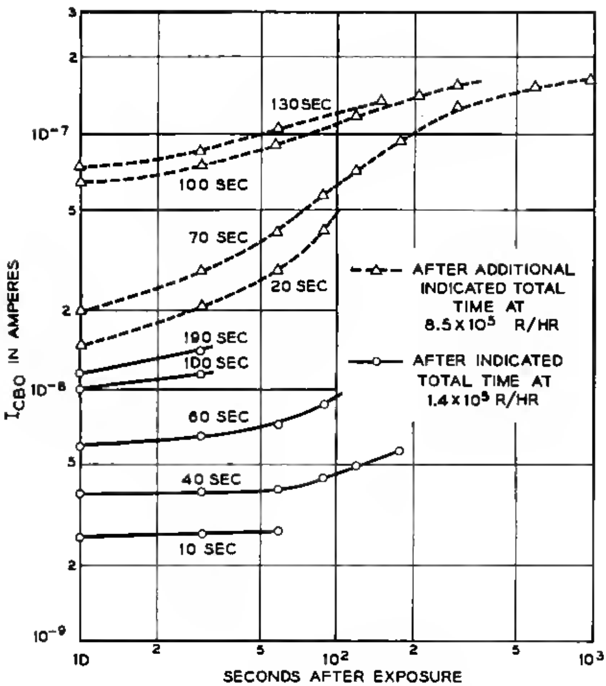

Fig. 21. — The pattern of collector current response in a grease-covered silicon transistor.

marked changes at about 10^4 rads, and another group having essentially no changes at 10^7 rads.

VII. TESTING AND SELECTION FOR TELSTAR DEVICES

The process of selecting the semiconductor components for use in the Telstar experimental communication satellite consisted of:

1. Qualification of design for reliability and performance as required in each application,
2. Fabrication,
3. Screening and preaging to assure satisfactory operation in the system environment,
4. Life testing,
5. Selection of the most stable devices.

At the time of recognition of surface effects from ionizing radiation (about October 1961), much of the life testing was already in process. Since the Telstar satellite was to orbit through the Van Allen radiation

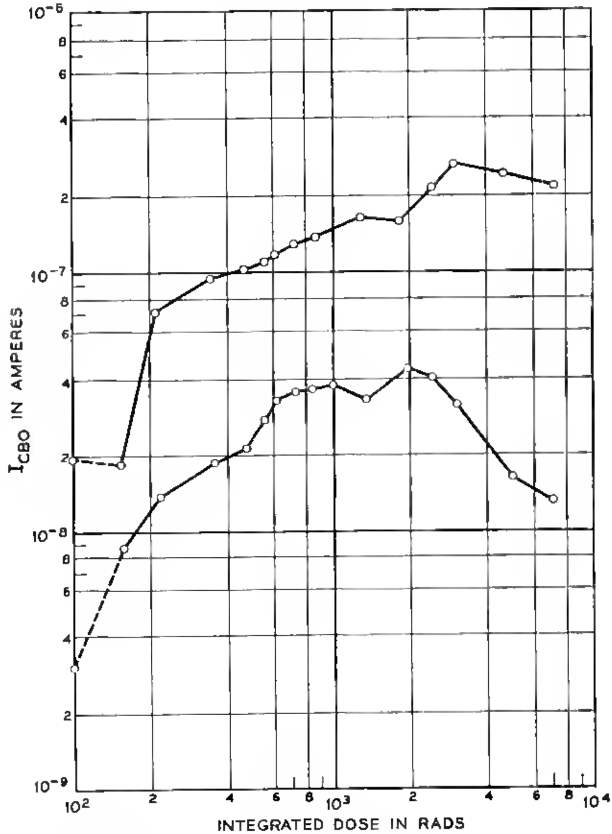

Fig. 22. — The response of a grease-covered silicon transistor under prolonged radiation at 5 rads/hr.

belt, the addition of radiation as an environmental factor was essential. Steps were therefore taken to determine the qualification of all types in the program and to study the screening and selection techniques that would be useful.

Fig. 23 shows a plot of the estimated ionizing radiation intensity for components inside a satellite, as a function of the shielding of the components from the external environment. These curves refer to the ionization produced by protons only and were developed from existing estimates of the Van Allen belt particle fluxes. The upper and lower limit curves reflect the uncertainties in this estimate. For shielding thicknesses of less than 0.1 inch the electron contribution to ionization should be considered as well, but for Telstar, typical components are shielded by

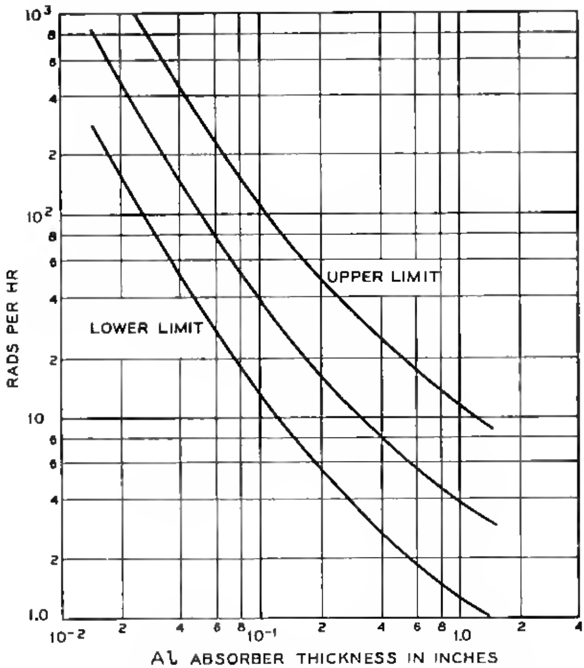

Fig. 23. — The maximum radiation intensity anticipated in space due to high-energy protons, as a function of the thickness of aluminum shielding.

the equivalent of 0.5 to 1.0 inch of aluminum and only high-energy protons are significant. The curves of Fig. 23 indicate that at this typical shielding, the radiation intensity would be a maximum of 10–20 rads/hr in the heart of the Van Allen belt. This results in a maximum average of 3–5 rads/hr over an entire orbit, considering Telstar's approximate 25 per cent effective exposure to Van Allen radiation.

With this estimate of the maximum radiation environment, all device types were given a gamma exposure at 8.5×10^5 rads/hr for one minute (the equivalent of at least three months in orbit), followed by at least one week at 3 rads/hr. Any device type showing evidence of change in either condition was replaced or subjected to individual selection or screening. Device types showing no change were considered satisfactory. All of these devices were subject to a 15-v reverse bias on the collector and an emitter current corresponding to the application.

The diffused silicon transistors F-54273 and F-54647 were used for experimental studies of screening and selection procedures. It is noted that the one-minute dose of 1.4×10^4 rads (at 8.5×10^5 rads/hr) is not

much beyond the variable Region 2 of Fig. 17 and should be very effective in providing a comparison between individuals. The study of the effectiveness of such a dose as a screening procedure was carried out through the following program:

1. Preradiation of a number of these transistors to screening exposures between 10 seconds and 6 minutes at 8.5×10^5 rad/hr and
2. Subsequent exposure at 5 rad/hr.

This permits an evaluation of the effect of the low dose rate after a screening dose.

Fig. 24 shows the collector reverse current measurements of two units from this program, these being generally typical of the results of all of the devices. In this case, the measuring equipment was limited in sensitivity to about 10^{-9} amperes and the initial values prior to radiation are shown at this value although they may have been somewhat lower. Unit No. 762 is representative of those units which suffered a relatively minor increase in reverse current during the preradiation dose. During the subsequent radiation at 5 rad/hr, this unit returned quite rapidly to its original value, remaining there until the dose became somewhat

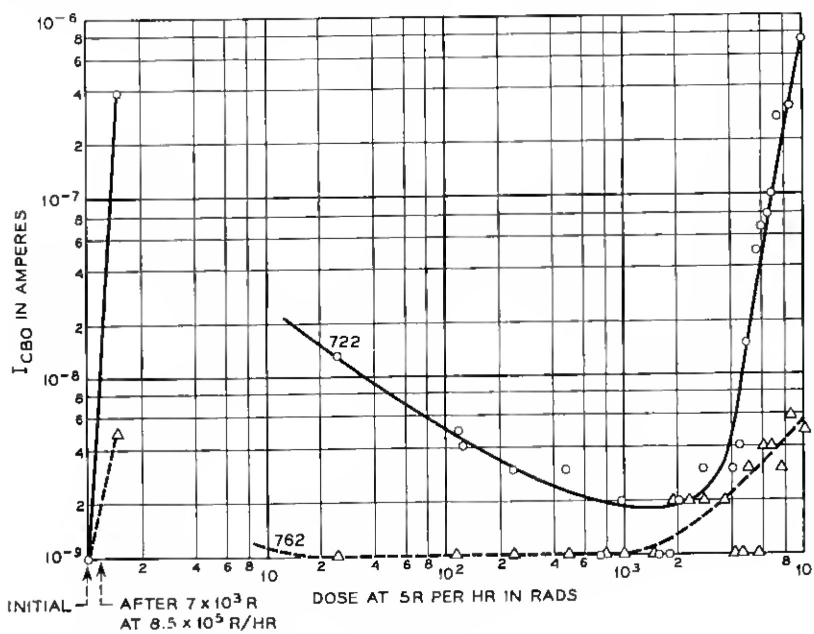

Fig. 24. — The typical pattern of change in I_{CBO} in low-level radiation after a screening dose.

greater than 10^3 rads, at which time it began to degrade in a fashion very similar to that expected from earlier tests. Unit No. 722 suffered a much greater change during the preradiation and took an appreciably longer time recovering toward its initial value. Before it fully recovered it reached the point of onset of final degradation and began to change quite rapidly. (A third type of response was seen in an occasional unit which degraded so severely during the preradiation that the subsequent low dose resulted in further increase in current and no recovery was evident at all.)

The influence of the screening dose on the distribution of onset of the final I_{CBO} degradation (at 5 rad/hr) is shown in Fig. 25 for four similar groups of 12 units each. One of these groups was irradiated at 5 rad/hr with no initial radiation at the high dose level. The other three groups were given an initial radiation at 8.5×10^5 rad/hr for different lengths of time to achieve the initial radiation dose indicated in the figure. It is seen that all of these distributions are essentially the same, indicating that the 5 rad/hr dose will cause a modification of the surface condition established by the high initial dose, causing the units to look eventually as if they had not received the initial dose. This is evidence of a contradiction to the principle of reciprocity of dose rate and time, in that the

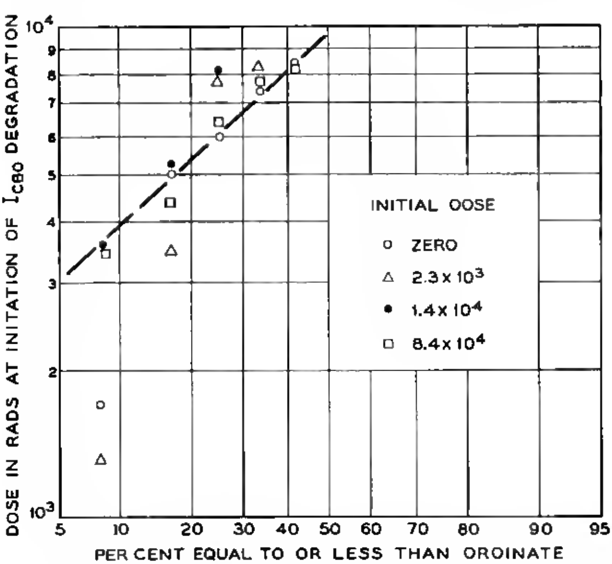

Fig. 25. — Distribution in dose for initiation of degradation with and without pre-irradiation.

additional dose added at the 5 rad/hr rate does not normally cause a continuation in the degradation produced in the initial dose.

Another point of interest in Fig. 24 is the comparison of the I_{CBO} value resulting from the preradiation dose with that subsequently occurring after an equal dose at 5 rad/hr. Inspection of the two curves on Fig. 24 reveals that the currents at 7×10^3 rad are approaching those resulting from the preradiation dose. Fig. 26 shows a plot of the results of all the units so treated. The dashed line indicates the one-to-one correlation between the two current values, those points to the right of the line representing the units which during the 5 rad/hr exposure did not develop reverse currents as high as those obtained in the initial dose. This line was not extended below about 4×10^{-9} amperes because this was approaching the limit of sensitivity of equipment which was then in use. It is noted that all but two of the significant readings fall on the side of the one-to-one correlation line corresponding to larger changes after the preradiation dose than after the subsequent low dose rate exposure.

In some cases the lack of correlation is quite significant, the currents after the low dose rate exposure remaining below 10^{-8} amperes although quite large changes were observed after the screening dose. In these

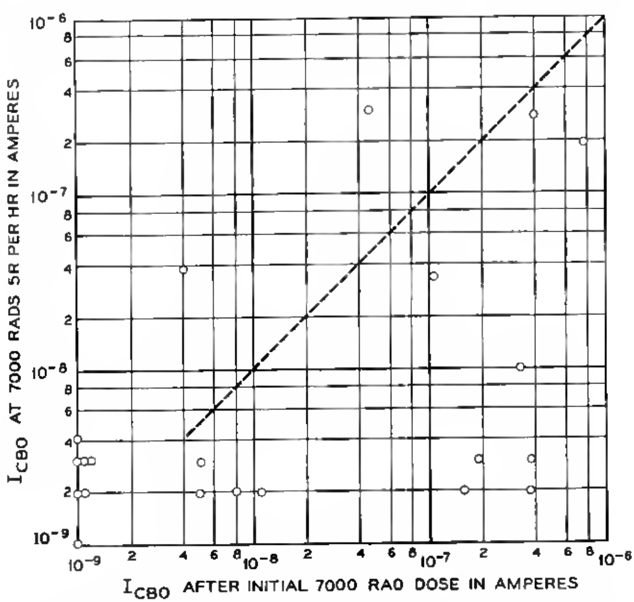

Fig. 26. — Correlation of change in I_{CBO} after a screening dose at 8×10^5 rads/hr with subsequent changes at 5 rads/hr.

units, however, the changes in current gain after the low dose rate exposure were found to be appreciably greater than in those units which were more stable in the initial screening dose. Consequently, it is found that selecting of those units with I_{CBO} less than 10^{-8} amperes after the screening dose would have eliminated 9 of the 10 units which subsequently degraded to either I_{CBO} values greater than 10^{-8} amperes or gains less than 50 per cent of the initial gain. Of the 12 units good in these respects after the low dose rate exposure, only two would have been eliminated by selection following the screening dose. It is thus shown that selection on the basis of I_{CBO} after a screening dose is effective for this device type.

An indication of the effect of this screening on the distribution in degradation of I_{CBO} under low-level radiation exposure is given in Fig. 27. Both distributions are of I_{CBO} after exposure, first to 30 seconds at 8.5×10^5 rad/hr and then to 10^4 rad at 5 rad/hr. One distribution is of

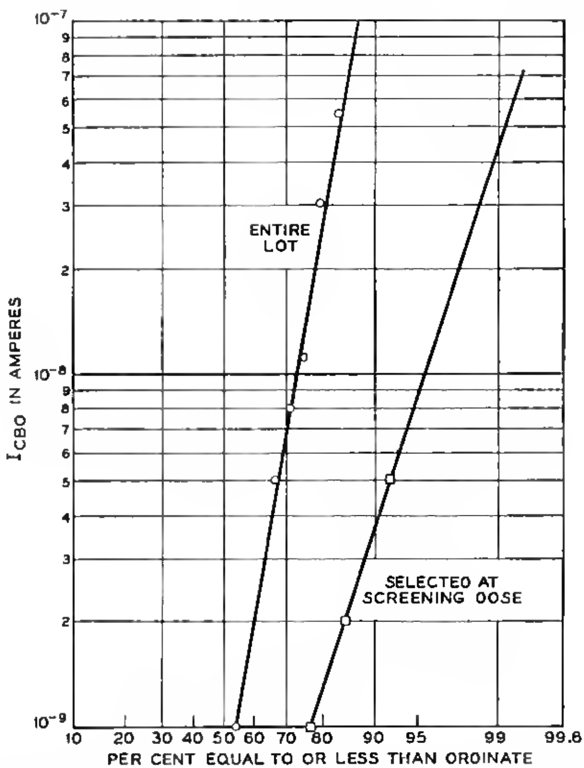

Fig. 27. — Distribution of radiation response in screened and unscreened devices.

the entire sample of devices and the other is of only those which were selected for I_{CBO} less than 10^{-8} amperes after the initial dose. It is seen that an appreciable improvement is achieved by the screening procedure.

VIII. SUMMARY

It has been found that changes can occur in semiconductor characteristics, because of surface effects of ionizing radiation in a device under electrical bias, at much lower doses than those required to produce surface effects in the absence of bias or to produce changes in the bulk of the semiconductor. These effects apparently arise from ionization in the gas of a device encapsulation and collection of ions on the device surface. The gas ions probably serve to produce and activate chemical species on the semiconductor which induce surface inversion layers that alter the junction characteristics. The chemical condition of the surface previous to irradiation is apparently involved in the process in a sensitive way. The effects observed depend on junction bias, envelope potential, and in many respects on total radiation dose rather than dose rate. The major features of these observations and of observations of the characteristic recovery of the surface effects after radiation under bias can be described by the ion-induced inversion layer model of the process.

In the time since the first direct observation of this effect, a comprehensive study of all types of semiconductor devices has not been attempted. Observations of several types, however, indicate that different types may respond quite differently to radiation, that the response may be quite dependent upon processing (and therefore upon production periods or batches), and that within a type the response may be quite variable between individual units.

One type of transistor was used for much of the experimental work of defining the radiation effect, and the I_{CBO} response was studied because the large changes facilitated comparative measurements. It is recognized that current gain and other surface-dependent characteristics can also be affected by radiation, and they should be observed in any evaluation of types, if critical in specific applications. It is hoped that the studies presented here will be a guide in formulating such evaluations.

It has also been found that at least some devices can be screened for sensitivity to radiation by means of a short-time, high-level dose, with correlation to subsequent low-level exposure results. Here, too, it is recognized that variations exist among types, and the usefulness of such screening operations should be evaluated for each type of interest.

It is hoped that further work will serve to provide more definitive results relating the radiation effects to a physical model and also to the

surface conditions or processes contributing to the effect. These preliminary results can at least serve to expose the problem and to suggest the lines of further study and action.

IX. ACKNOWLEDGMENTS

The material presented here includes the contributions of many of the authors' colleagues. Of particular significance have been the efforts of E. P. Moyer, E. R. Schmid, and J. Lange, of Bell Laboratories and G. L. Miller of Brookhaven National Laboratory.

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